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DEATH HURTS, BUT IT ISN'T FATAL: THE POSTEXIT DIFFUSION OF KNOWLEDGE CREATED BY INNOVATIVE COMPANIES

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There is little understanding of whether a firm's innovative knowledge dies with it or if instead significant diffusion of knowledge occurs even after a firm exits an industry. Theoretical predictions about the differing effects of firm exit on private and public knowledge and implications for interfirm knowledge transfer are forwarded. We investigated main and moderating effects of a firm's exit from the disk drive industry on knowledge diffusion to other firms, finding evidence that the ability to use a firm as a template plays a critical role in successfully replicating its knowledge. Absent this template, knowledge "stickiness" reduces knowledge diffusion.

In 1999, despite millions of dollars of investment and a portfolio of innovative technologies, flat panel display manufacturer Optical Information Systems (OIS) shut down operations, unable to achieve commercial success. Although OIS failed, its technology lived on. A letter by the firm's former director of advanced technologies to the editors of the magazine *Information Display* reported that even after the firm's exit, OIS technology continued to make waves in the flat panel industry, with many of its patents covering processes that became mainstream technology. The letter then cited specific innovations by other firms that had built on OIS breakthroughs. Although the firm had exited the industry in spite of its technological strength, it left a lasting legacy for the industry's technology.

Is the OIS story unusual, or does it highlight a regular occurrence? Since technological expertise is an important determinant of firm success (Jovanovic & MacDonald, 1994; Teece, 1986), it could be argued that firms that exit an industry are typically lacking in this important area and thus have little impact on the technological progress in the industry. This formulation would imply that firms like OIS are outliers and that diffusion of the knowledge they create is generally low, both before and after they exit an industry. However, there is strong evidence that many companies exit despite having developed innovative knowledge (Golder & Tellis, 1993; Katz & Shapiro, 1985) and that a lack of complementary assets (Teece, 1986) often results in firms' untimely deaths. If this is the case, then firm exit will not be perfectly, negatively correlated with technological superiority. To the extent that some firms exit in spite of having created technological knowledge, other firms may attempt to build on the knowledge created by departed firms.

Although the issue of whether other firms subsequently capitalize on knowledge created by companies that exit an industry remains underresearched, it is important to investigate for several reasons. First, 8 to 10 percent of all companies leave an industry in an average year (Agarwal & Gort, 1996), but their exit may nonetheless create economic benefits and impact social welfare (Dunne, Roberts, & Samuelson, 1988; Knott & Posen, 2005). Many of these companies may have been technologically innovative and are thus underexploited sources of technological progress and increases in social welfare. Further, in some industries, substantial public investment may have been made in these companies, through either tax incentives or direct funding. Does the value of that investment depend on the commercial success of the firm receiving the funding, or can other firms that remain commercially viable subsequently harness the resulting innovation?

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Theoretically, since the issue relates to interfirm knowledge transfer under the most challenging conditions, it offers an opportunity to examine the issues that may be relevant when firms seek to capitalize on other firms' technologies. The traditional view of knowledge highlights the positive externalities inherent in knowledge creation and the nonrival, nonexcludable nature of information, particularly when it is embodied in patents (Arrow, 1962; Griliches, 1979; Jaffe, 1986). Patents represent codified knowledge that has been publicly revealed through the publication of patent documents, thus enabling the use of the knowledge by firms other than the originators (Jaffe, 1986; Spence, 1984). In contrast, an alternative view emphasizes that knowledge may have private as well as public aspects (Nelson & Winter, 1982). These private aspects (Nelson & Romer, 1996) impart knowledge "stickiness" (von Hippel, 1994), a consequence either of the embeddedness of innovations in organizational routines and teams (Martin & Mitchell, 1998; Nelson & Winter, 1982) or of causal ambiguity (Lippman & Rumelt, 1982; Rumelt, 1984). Restriction of interfirm knowledge transfer is the outcome. Researchers have found that significant tacit knowledge resides within the social structures of organizations, since innovation is the result of concerted and directed efforts by entire teams of employees.

Our paper builds on the complementarity of the private and public components of knowledge (Nelson, 1990) to examine how the lack of accessibility of private knowledge affects subsequent diffusion of the public knowledge embodied in a firm's patents. Exit means both loss of the private knowledge embodied in a firm and loss of the possibility of using the firm's activities as a template (Winter & Szulanski, 2001). Examining the effect of firm exit on knowledge diffusion can thus shed light on the importance of private knowledge as a facilitator of the diffusion of public knowledge. Importantly, we address the competing explanation that firm exit may represent a lack of relevance of the knowledge and develop hypotheses for the interaction of firm exit with variables associated with the greater presence of private knowledge. Thus, we contribute to the literature on the extent of knowledge spillovers between firms by discussing how private knowledge may serve as a boundary condition for the public knowledge a firm creates. Our examination of the postexit diffusion of knowledge also complements studies of the importance of geographical location (Agrawal, Cockburn, & McHale, 2003; Audretsch & Feldman, 1996) and employee mobility (e.g., Rosenkopf & Almeida, 2003) for accessing private knowledge and reducing the tacitness and stickiness of knowledge (von Hippel, 1994).

To the best of our knowledge, no study has systematically examined the impact that the exit of a firm has on the diffusion of the knowledge it has created. The empirical setting of our study is the hard disk drive industry, because of its technological intensiveness and the availability of the data necessary to examine our research questions (Christensen, 1993). We define firm exit, or "death," as a firm's having ceased operations in the disk drive industry, excluding firms that were acquired. We ensure that for diversified firms, exit from the industry was concomitant with a cessation of their innovative activity related to the industry. We also investigate the possibility that firms that exited were insignificant in the development of hard drive technology and do not find this to be the case. Using patent citations as a measure of knowledge diffusion, we examine the effects of firm exit not only on the overall patent-citation life cycle, but also on the relationship between characteristics of an innovation and its diffusion to other firms.

We find support for our hypothesis that exit impairs the ability of other firms to draw on the knowledge generated by a firm; firm exit results in a significant decline in citations received by a focal patent. Further, we show that firm exit interacts with variables associated with more embeddedness of knowledge in a firm's private routines (firm age at time of patenting, degree to which an innovation built on the innovating firm's internal knowledge base, and number of inventors) to have a negative impact on the patent's citations. As a result, we find broad support for our hypotheses that the higher the private component of a firm's knowledge, the more pronounced is the negative impact of the firm's exit on subsequent citations. However, the firm's exit—the death of its industry-related activity—does not halt *all* further use of its technology, and the effect of exit on subsequent citations attenuates over time. Thus, firms that exit an industry provide spillover benefits to others, in keeping with the findings of Knott and Posen (2005).

THEORY

Private and Public Components of Knowledge

The idea that as firms pursue new knowledge, they create a public good dates back to Arrow (1962). Subsequent work in the area has discussed the implications of the nonrival and nonexcludable properties of knowledge for its subsequent diffusion, since both aspects increase the likelihood of

another firm benefiting from the knowledge created by a focal firm. Because investments in knowledge-creating activities by a firm also increase the human capital of its employees (Becker, 1964), employee mobility has been identified as a key mechanism for knowledge diffusion (Almeida & Kogut, 1999), though knowledge diffusion can also occur through other mechanisms, including codification, reverse engineering and scientific reproduction, and formal or informal interpersonal contacts (Arrow, 1996).

However, much attention in the last 20 years has also been paid to the tacit aspect of knowledge, particularly that which is team-based and socially embedded in firm routines (Nelson & Winter, 1982). Highlighting the fact that not all the innovative knowledge firms create is public, Nelson (1990) argued that firms generate innovative knowledge by combining generic, public knowledge with specific designs and practices that are private and known only to their creators. The success of other firms in replicating and building on the knowledge created by a firm thus depends on their ability to understand the private knowledge within which the public knowledge is embedded (Rosenberg, 1982).

The private aspect of knowledge results in knowledge "stickiness" (von Hippel, 1994) due to causal ambiguity and the embeddedness of innovations in individual human capital (Becker, 1964), and organizational or team-based rules and routines (Lippman & Rumelt, 1982; Nelson & Winter, 1982; von Hippel, 1994; Szulanski, 1996). For example, causal ambiguity, the "basic ambiguity concerning the nature of the causal connections between actions and results," impedes duplicating and extending another firm's innovative knowledge (Lippman & Rumelt, 1982: 420). It may be unclear which of the multiple research efforts that a firm engaged in ultimately led to its innovative success. This lack of clarity may in part be because the knowledge resides at different levels within the firm, including individual inventors, research teams, and routines for combining complementary resources. In addition to occurring at different levels, the private knowledge may vary in nature over organizational levels. An individual inventor may possess tacit knowledge about the underlying scientific basis of an innovation. The ability to manage the complexities of interactions within a team is likely to reside largely within team routines, which no single individual may understand completely. The overall research and product line trajectory is more likely to reside at the level of the firm. Also, the relative importance of private knowledge at different levels is contingent on the nature of a particular innovation. For example, for a leading-edge technology, the tacit knowledge of individuals may be paramount, but for an innovation requiring a large team of inventors, the routines of the innovating team may be dominant.

Since most innovations embody private knowledge at multiple levels, ambiguity results regarding the conditions under which their technologies can be gainfully applied (Nelson & Winter, 1982). It may also be difficult to judge the potential value of an innovation (Podolny & Stuart, 1995). Greater ambiguity on each of these dimensions limits the degree to which a firm other than the source firm can build on an innovation, even if the other firm has access to the public component of the relevant knowledge.

Thus, the received literature suggests that private and public knowledge are complementary requisites for the creation of new knowledge; in order to understand the private aspects of another firm's innovative knowledge, a firm must overcome the associated embeddedness and causal ambiguity. It can attempt to do so by undertaking its own research efforts to build the required understanding internally (Cohen & Levinthal, 1990). However, vicarious learning—learning from the experience of others through observation (Cyert & March, 1963)—is likely to be less costly than reinventing and learning experientially (Schulz, 2003). Since transferring knowledge often requires access to tacit organizing principles that are not easily articulated, the opportunity to consult a working example can be very valuable (Winter, 1987). As Winter and Szulanski wrote, "The recreation of a complex, imperfectly understood, productive routine is often a protracted process that involves many references to an existing working model" (2001: 742). This statement is consistent with Haunschild and Miner's (1997) finding that firms faced with uncertain technology rely on observing the organization that is the source of the technology for clues on how to organize and act. In essence, a source firm's routines and subsequent actions serve as a template for those wanting to emulate its innovative activities. Interacting with or observing the source firm enables understanding which innovative trajectories were considered important to pursue, and what associated research efforts were subsequently emphasized or dropped. Other firms also gain valuable insights on how to manage roadblocks that arise in advancing an innovation (Almeida & Kogut, 1999). Observing what innovations eventually become commercial products provides a way to evaluate the commercial potential of an innovation (Arrow, 1996). Thus, observing an innovating firm's subsequent actions helps other firms in de-

termining the level(s) at which the private knowledge resides, deciding what innovative knowledge is worth replicating and extending, assessing the hurdles, and assessing the directions to follow during replication and extension. The importance of such direct or indirect interaction with an innovative firm has been well established in the vast literatures on learning in alliances (Dyer & Singh, 1998; Gulati, 1998), social networks (Burt, 1992; Granovetter, 1985), and knowledge spillovers via geographical proximity (Alcácer & Gittelman, 2006).

Effect of Firm Exit on Knowledge Diffusion

The preceding discussion emphasizes the importance of the continued existence of innovative firms for the diffusion of their knowledge—the firms themselves serve as templates, because their routines embody the interaction of the private and public components of their knowledge. Thus, just like any artifact, whether a hammer or a computer, embodies knowledge that new producers of similar artifacts can use (Cowan, David, & Foray, 2000), a focal firm's existence and activity represent embodied knowledge that subsequent developers can rely upon while building on their own knowledge. We now argue that the exit of a firm removes the possibility of direct or indirect interaction with the firm as a whole, thus limiting the extent to which other firms can capitalize on its knowledge, even if its employees and the codified knowledge are available.

In developing our hypotheses on the effect of its exit on the diffusion of a firm's knowledge, we note two issues. First, we deliberately focus on knowledge that is already codified and information available to other firms via patents. Patent data provide a stringent environment within which to test the importance of private knowledge and firm existence. If the private knowledge of a firm is not an important complement to the explicit/codified knowledge available within patents, then firm exit should have no appreciable impact on the rate at which other firms use and cite the patented knowledge. Second, we focus on *source* firm characteristics only, and not on recipient firms' capabilities and strategies for harnessing the knowledge that may affect their absorptive capacity (Cohen & Levinthal, 1990). Thus, we are interested in "average" postexit diffusion of knowledge and do not address differences among citing firms in their control over complementary assets required to commercialize disk drive products, or in the relevance or magnitude of their internal R&D efforts or hiring practices.

The exit of a firm removes the opportunity to observe and interact with the firm, which, as indicated above, is important for understanding the private aspects of the knowledge created by the firm. Although access to the public good aspect of the knowledge remains (via reverse engineering and reliance on codified knowledge), the firm's activities can no longer serve as a template for other firms seeking to build on its knowledge. After firm exit, the private knowledge that resides at levels other than at the individual inventor level is likely to undergo substantial disruption and loss. It may not always be feasible to protect the private knowledge held at the team level, and the potential scattering of the firm's innovative personnel to other firms may additionally complicate efforts to use social networks as a way of gathering information on the firm. Even when all (or most) of a team are able to move en masse to another firm, they face the challenge of functioning under a new management and incentive system. At the firm level, it is not possible, postexit, to observe how the innovating firm would have configured its complementary resources to build upon an innovation. Furthermore, since the firm's commercialization efforts have stopped, other firms cannot use observations about what innovations eventually become commercial products to evaluate the commercial potential of an innovation. The complementarity of the private and public components of the knowledge a firm has created leads us to expect that its exit will reduce other firms' ability to capitalize on its knowledge.

We note the possibility that, since technological capabilities are positively related to firm survival, exiting firms represent lower levels of technological prowess. However, such a correlation would impact the *levels* of citation received by a firm's patents; there would be no reason to expect a change in the *rate* of citation before and after firm exit. There are two other reasons, though, that are consistent with the observation of a postexit decrease in firm citations. Patents often represent strategic behavior (Ziedonis, 2004), and it may be argued that firm exit reduces the threat of patent infringement litigation. If the firm that created a patent is no longer around to defend the relevant intellectual property, the risk that litigation will occur if subsequent patents omit its citation is reduced. Given the market for intellectual property (Anton & Yao, 2002; Mann, 2005), other firms often acquire an exiting firm's patent rights; thus it is not clear whether there is indeed a substantial decline in the risk of litigation. Finally, a firm's knowledge may lose relevance when it exits, either because of exogenous shocks or the exit's perceived signal value. Although we explicitly addressed the above

competing explanations both in our choice of empirical context and in our testing of our first hypothesis, we cannot discount the possibility that the decline in the citations associated with firm exit may be a result of a perceived reduction in either the risk of litigation or the relevance of the patented knowledge. Since all these reasons point to a postexit decline, we hypothesize:

Hypothesis 1. Subsequent citation (use) of a patent by other firms in an industry is negatively impacted by the patenting firm's exit from the industry.

We note, however, that if factors related to relevance or to risk of litigation, rather than to the accessibility of private knowledge, are the true drivers of our hypothesized decline in citations after firm exit, there should be no difference in the rates of knowledge diffusion among characteristics associated with varying degrees of private and public components of knowledge. In the following section, we develop interaction hypotheses that enable us to isolate the role of accessibility of private knowledge in determining postexit diffusion.

Interaction of Firm Exit with Knowledge Characteristics

The importance of the private knowledge held by a firm to the diffusion of its patented knowledge will vary with the characteristics of an innovation. The greater the private component of knowledge, the greater will be the effect of firm exit on the subsequent diffusion of knowledge. We examine the interaction of exit with four variables that have been associated with the embeddedness of knowledge in a firm's private routines: the age of the innovating firm, the degree to which the innovation built on the innovating firm's internal knowledge base, the number of inventors, and the diversity of technologies the innovation drew upon. Each variable influences the importance and/or accessibility of the innovating firm's private knowledge. Since the loss of the innovating firm as a template makes it more difficult to replicate the firm's private knowledge, we expect that exit will have a larger negative impact the more important or inaccessible the private knowledge was for that innovation. We now examine each variable in turn, exploring its relationship to the role of the private knowledge associated with innovations.

It is well established that the embeddedness of innovations in organizational routines increases with a firm's age owing to greater formalization of structures and encoding of lessons in routines (Levitt & March, 1988; Nelson & Winter, 1982). A firm's core capabilities, particularly those related to technology, are developed through learning and experience, and this "path dependency" implies that older firms have higher stocks of private knowledge (Sorensen & Stuart, 2000). This is because older firms have gone through a longer process of learning and have stored past learning in behavioral rules and routines (Dosi, Teece, & Winter, 1992; Nelson & Winter, 1982). Thus, it may be difficult to build on established firms' capabilities as they are more likely to be embedded in networks of intrafirm relationships. Building on an older firm's knowledge may require a recipient firm to observe or interact with the older firm more than would be necessary with a younger source firm, to learn both its rules and routines and how its subsequent innovations built on its earlier ones. Thus, the older a firm was at the time of a patent, the greater will be the impact of the loss of the firm as a template.

A similar logic applies to innovations that result from a firm building on its prior innovations (Jaffe & Trajtenberg, 2002). These innovations draw heavily on a firm's internal knowledge base rather than on the knowledge of others and are said to reflect "localized search" (Anderson & Tushman, 1990). They will therefore be closely bound within the routines and culture of the innovating firm (Nelson & Winter, 1982). Further, they are likely to be couched in the idiosyncratic language of the firm (Arrow, 1974). As such, innovations that draw heavily upon a source firm's internal knowledge base will be highly tacit and difficult for others to imitate and extend, particularly after the exit of the source firm. Again, we anticipate a larger postexit drop in the diffusion of an innovation if that innovation drew heavily on a firm's internal knowledge base.

Since older firms and firms that draw on their internal knowledge bases will have more private knowledge, we hypothesize:

Hypothesis 2. The older the patenting firm is at the time of a patent application, the more negatively the firm's exit impacts subsequent citation (use) of that patent by other firms.

Hypothesis 3. The more related a patent is to the patenting firm's internal knowledge base, the more negatively the firm's exit impacts subsequent citation (use) of that patent by other firms.

The larger the number of inventors associated with an innovation, the larger is the pool of mobile employees upon the exit of the firm from the industry. Indeed, a source firm's employees may continue to build on a technology once they join (or create) other firms, and this condition might lead

one to argue for a greater diffusion of knowledge after an exit. However, the greater the number of inventors in a research team, the more numerous the necessary interactions between individuals, and the more embedded the innovation in a complex web of relationships (Van de Ven, 1986). When a team of inventors is large, the range of specialized skills represented on it is also often large (Schilling, 2006; Valentin & Jensen, 2002). Such a large team represents not simply more interactions, but increasingly complex ones. Maintaining effective communication in a group whose members have diverse technical backgrounds is a complex challenge (Pfeffer, 1981) requiring the development of routines and languages that span technical specializations.

Thus, the greater the number of inventors on a team, the greater the degree of private knowledge that is embedded in the team and its firm. This increase in private knowledge increases the importance of the continued existence of the knowledge-creating firm for other firms seeking to build on its innovations. Absent the routines of a departed firm, other firms and their individual inventors will, we believe, have limited ability to replicate the exiter's activities. Further, the higher the number of inventors on a team, the more difficult it is for the entire team to be hired or easily assimilated by another firm. Thus, although individual employees may be able to leverage their knowledge at their new place of employment, team- and firm-level private knowledge may be more difficult to replicate. Overall, we posit that a firm's exit will have a stronger impact on the diffusion of knowledge created by a large team of inventors than it will have on the diffusion of knowledge created by a small team. Accordingly,

Hypothesis 4. The larger the team of inventors a patent has, the more negatively the patenting firm's exit impacts subsequent citation (use) of that patent by other firms.

Similarly, innovations that draw upon a wide range of underlying technologies (e.g., organic light-emitting diodes, which require expertise in electronics, organic chemistry, and materials science) tend to be stickier than those that are extensions of a narrow field of knowledge, since they may require exploration rather than exploitation (March, 1991). Knowledge that synthesizes divergent knowledge bases tends to be highly original (Trajtenberg, Henderson, & Jaffe, 1997), and combinations of multiple fields tend to occur at the technological frontier. Knowledge surrounding such breakthrough research is likely to be highly tacit and therefore hard for outsiders to imitate (Nelson & Winter, 1982). Further, just as tacit expertise is vital to the management of products with many interacting components (Chesbrough & Teece, 1996), it is also important in the management of research that draws on many interacting technologies. Thus, direct interaction and vicarious learning should be especially important for the diffusion of technologies that draw on a wide range of technologies. This argument implies that firm exit will have a greater detrimental impact on the subsequent use of an innovation that embodies a wide range of technologies.

Hypothesis 5. The more diverse technologies a patent draws upon, the more negatively the patenting firm's exit impacts subsequent citation (use) of that patent by other firms.

DATA

To address the research questions above, we needed to examine knowledge diffusion across firms for the census of corporations that entered (and exited) an industry. We tracked such knowledge diffusion as the subsequent use of a firm's technology by other firms via patent citations. In doing so, we followed a large body of research that has used the citations a patent receives as an indication of the degree to which subsequent innovations have built upon it (Jaffe & Trajtenberg, 1996; Katila & Ahuja, 2002). The chief advantage of using patent data for our purposes was that these data reliably capture subsequent use of innovative knowledge by other firms. An inventor who files a patent application is required by law to list all "prior art" of which she or he is aware. Unlike academic citations, these citations to earlier work have the important legal function of limiting the scope of the property right granted to the patent. Further, the patent examiner in charge of the application, who is an expert in the technological area of the patent, can add citations that the inventor may have missed or concealed. This practice reduces the probability that irrelevant patents will be cited or that relevant patents will be omitted. Not every citation represents awareness of the cited patent within an organization filing the citing patent, since the patent examiner could have added the citation (Alcácer & Gittelman, 2006; Cockburn, Kortum, & Stern, 2002); however, a variety of studies have confirmed that patent citations are an accurate, though noisy, indicator of actual knowledge flows (Jaffe, Trajtenberg, & Fogarty, 2002).

Context: The Disk Drive Industry

Given the data requirements of a study on knowledge diffusion before and after the exits of firms, the industry chosen for our empirical context needed to conform to certain boundaries. First, it had to be relatively technologically intensive, because technologically intensive industries have higher rates of knowledge generation, and hence higher rates of knowledge transfer. Second, we needed longitudinal data on firms that were successful in the chosen industry and those that ultimately exited it. Third, although the industry had to experience significant technological change, it needed to have some stable underlying knowledge base—that is, knowledge that continued to have relevancy over time. We selected the hard disk drive industry for our empirical context since it conformed to both the theoretical and empirical requirements of the study.

Disk drives are magnetic information storage devices used in computers. In 1973, IBM pioneered the 14-inch Winchester, the first completely sealed and removable disk drive, and the disk drive industry has since experienced rapid technological evolution (see Christensen [1993, 1997] for a detailed industry history). The industry experienced significant levels of both entry and exit in the relevant period, and it has followed the typical industry life cycle of introduction, growth, shakeout, and maturity (Gort & Klepper, 1982). Since every productive firm was included in our data, regardless of size, the data do not suffer from a survivor bias.[1] Many of the entering firms represented employee entrepreneurship and, thus, interfirm knowledge transfer (Agarwal, Echambadi, Franco, & Sarkar, 2004). Additionally, as McKendrick, Doner, and Haggard (2000) documented, both the employee mobility and interfirm spillovers that shape new firms' technology and location choices are extensive in the disk drive industry.

With regard to the pace of technological change, we knew that numerous architectural, modular, and incremental innovations occurred in this industry after the radical innovation embodied in the Winchester drive. Importantly, although the architectural innovations (the introduction of smaller diameters) heralded access to new customers and submarkets, these innovations employed off-the-shelf component technology, and "no new technology [was] involved in these disruptive products" (Christensen, 1993: 191). As a result, the underlying knowledge base for creating disk drives remained largely unchanged, even though market disruptions due to new customer bases caused several technologically superior firms to exit the industry.

Finally, despite the validity of caveats regarding the use of patents as a measure of both inventiveness and knowledge diffusion (Jaffe, Trajtenberg, & Henderson, 1993), a strong and significant correlation ($r = .57$, $p < .001$) exists between the patenting activity of firms and their technological capabilities as measured by the areal density of their disk drives, a measure commonly used for technological performance in studies of this industry (Agarwal et al., 2004; Christensen, 1997). Thus, the disk drive industry was a particularly appropriate setting for our study.

Data Sources

For firm-level information, we relied on the *Disk/Trend Report,* a market research publication that tracked annual productive activity by all firms, public and private, in the industry from 1977 to 1997, the period studied here. The detailed reports on each firm provided in *Disk/Trend* were used to track entry and exit dates. Numerous prior studies have used the rich, reliable data provided by this source in empirical testing (Christensen, 1993), and these studies attest to the comprehensiveness of the data source, particularly its inclusion of small and private firms. Our own checks of these data against external sources (e.g., Lexis-Nexis, the *Directory of Corporate Affiliations*, and the *Thomas Register of American Manufacturers*) confirmed the inclusiveness of the database and the accuracy of the entry and exit dates of the firms and their indicated status as diversified or disk-only manufacturers (Agarwal et al., 2004; King & Tucci, 2002; Lerner, 1997). For information on patenting by firms operating in the disk drive industry, we relied on data drawn from the National Bureau of Economic Research (NBER) Patent Citations Data File (Hall, Jaffe, & Trajtenberg, 2002) and the database MicroPatent U.S. The choice of patent classes to include in our sample involved a trade-off. Thompson and Fox-Kean (2005) and Henderson, Jaffe, and Trajtenberg (2005) discuss issues that pertain to problems in broadly or narrowly defining a technology through the choice of patent classes and subclasses. On the one hand, including a broader range of patent classes implies that a sample will be more inclusive of inventive activity and will represent more patents. On the other hand, the broader the range of patent

[1] We note that our data do not cover the first three years of the industry. However, industry life cycle studies (Agarwal & Gort, 1996; Gort & Klepper, 1982) indicate that firm exit is very infrequent during such periods, so we did not expect our results to be affected by the nonavailability of data during these years.

classes, the more likely it is that the patents have application outside one's industry of interest.

We adopted a conservative strategy and restricted the pool of patents to the class most relevant to hard disks: U.S. patent classification code 360, dynamic magnetic information storage or retrieval. Since the NBER data only list the first, not all, classifications of a patent, we augmented these data with the MicroPatent database to ensure that all patents that were listed under code 360 were included in our data. The 360 patent class as a whole remained stable and relevant over the period of our study, though there was considerable reorganization of the subclasses it contained, as is typical for technologically intensive patent classes (Henderson et al., 2005). Since we used the three-digit classification, the reorganization of subclasses had no effect on our analysis. An investigation of the patents held by "pure-play" hard disk drive manufacturers—firms that do nothing but make hard disk drives (Agarwal et al., 2004; King & Tucci, 2002; Lerner, 1997)—confirmed that 57 percent of their patents were assigned to patent class 360. The next two largest classes that the pure-play manufacturers were assigned to were 348 (television) and 399 (electrophotography). Since the majority of the patents assigned to these classes would have been unrelated to hard disks, we did not include these in our sample.

Data Description

The data from the above two sources were cross-checked against the information from the *Disk/Trend Report*. We checked the data manually to rectify any inconsistencies in how firms were listed in the two patent databases. Further, for firms that had subsidiaries, we used the NBER COMPUSTAT data file, which gives the parents of subsidiary companies, to ensure that patents assigned to subsidiaries were also included.[2] We selected all disk-drive-related patents assigned to a firm that had application dates between 1976 and 1997. Finally, we identified all patent citations for these patents in each year until 1999, the final year in the NBER Citations database. This process generated a pool of 5,179 patents in 57 firms that had at least one disk-drive-related patent. The final data set consists of 43,161 patent-year observations—for instance, patent 4,933,785 observed one year after the year in which it was applied for, patent 4,933,785 observed two years after its application year, and so forth—in an unbalanced panel that contains all years between a patent's application year and 1999. For every observation, the data contain detailed characteristics regarding both the patent and the firm to which it was assigned.

In particular, of the 57 firms included in our data, 40 exited the industry in the time period under analysis. These firms were distributed relatively evenly on status as diversified or pure-play disk drive manufacturers; 28 firms were diversified, and 29 were pure-play manufacturers. However, as would be expected on the basis of size differences, the larger diversified firms patented significantly more than the smaller pure-play firms. Among the firms that survived (exited) the industry, 9 (19) were diversified firms and 8 (21) were pure-play firms. Importantly, the exits of the diversified firms were accompanied by a 93 percent decline in their disk-drive-related patenting activity. Indeed, 13 of the 19 firms had zero patents related to disk drives after exit. Consequently, even for the diversified firms in the industry, exit from disk drives clearly meant the "death" of their disk-drive-related activity and, thus, loss of a template for other firms in the industry.

Variables in the Study

We now turn to a description of the chief variables in the study, which are summarized in Table 1. Our dependent variable, *citations received*, was the number of citations received by a focal patent from firms other than the one holding the patent in each year after its application year. We used application year to ensure consistency with other studies of knowledge spillovers and diffusion that have used application rather than grant year to better track the vintage of a technology (e.g., Jaffe et al., 1993; Thompson & Fox-Kean, 2005). This variable measures interfirm knowledge flows in a manner similar to that used by Song, Almeida, and Wu (2003) and Rosenkopf and Almeida (2003). However, we note that as Alcácer and Gittleman (2006) showed, early citations (particularly those to work that has not yet received a patent) are more likely added by patent examiners and thus are not truly reflective of knowledge flows. We omitted self-citations—citations by a firm to its own earlier patents—since we were primarily interested in interorganizational knowledge transfer. This omission was also conservative, since the mechanisms driving self-citations may differ from those behind citations by other firms (Caballero & Jaffe, 2002; Tra-

[2] We note that it is very likely that not *all* subsidiary patents are included in our data, given the limitations of the NBER database. Specifically, the NBER data capture subsidiary structure in 1989, and only for those firms that were publicly listed on a U.S. exchange.

jtenberg et al., 1997). Further, since self-citation was not possible after a firm had exited the industry, including self-citations could have falsely magnified the impact of firm exit on knowledge transfer.

Firm exit was defined as the cessation of a firm's operations in the disk drive industry. Since acquisitions represent a change in ownership and differ substantially from exits, we did not include acquisitions in our study. The indicator variable, *exit*, was set to 1 for observations occurring after a patenting firm had exited the industry and to 0 otherwise.

To capture the impact of firm exit on the effect of our independent variables, we interacted exit with each of them. The independent variables defined characteristics of a patent and patenting firm at the time the firm applied for the patent. We calculated *firm age* at the time of a patent by subtracting the year of firm entry into the disk drive industry from the application year of the patent. A patent's *internal focus* was the proportion of citations in it that were to the firm's own prior patents and corresponded to the self-citation ratio calculated in the NBER database.[3] The larger the value of this variable, the more an innovation drew upon the firm's internal knowledge base. *Number of inventors* was the number of inventors listed on a patent application, used here as an indication of the size of the team involved in the innovative research being patented. *Range of technologies combined* corresponded to the originality score calculated in the NBER data and first suggested by Trajtenberg and colleagues (1997). By counting the number of citations a patent makes within each of the three-digit patent classes, this measure captures the degree to which the patent draws upon a wide range of technological areas. The measure is defined for patent i as:

$$1 - \sum_{k=1}^{K} \left(\frac{NCITED_{ik}}{NCITED_i} \right)^2, \qquad (1)$$

where *Ncited* represents the number of patents cited by a focal patent and k indexes three-digit patent classes. Patents based on research that draws upon a wider range of technological roots have a larger value on this variable. Hall (2002) suggested a modification of this measure to reflect the fact that patents with few citations are less likely to cite a broad range of classes. The modified measure multiplies the original measure by $n/(n - 1)$, where n is the number of citations made by a patent. We used the modified measure, having confirmed that our results were robust to the choice of measure.

Among the control variables, we included firm dummies, to control for unobserved heterogeneity that might affect citations to all of a firm's patents, and application year dummies, to control for potential cohort effects. To control for the effect of *citation lag*—the difference in time between the application years of the citing and original patents—we used a set of indicator variables, *citation lag 1* to *citation lag 24*, setting the appropriate variable to 1 for observations of the 1st through the 24th year after a patent was applied for. Additionally, we included two control variables for the quality of an innovation and an innovating firm: maturity of technology and recent technological activity. *Maturity of technology* was the number of citations to prior patents made by a focal patent, divided by the number of claims the patent made (a measure of the technological space a patent occupied). More citations to prior art per claim indicates a more developed or mature technological field (Lanjouw & Schankerman, 2003). A mature technology may be easier to understand (Sorensen & Stuart, 2000), yet it may also simply be of less interest to other firms. Further, because there is likely to be a larger stock of innovations for a more mature technology, any given innovation would be, ceteris paribus, less likely to be built upon. *Recent technological activity* was computed as the mean number of disk-drive-related patents a firm had applied for in the prior three years. For patents applied for in the second or third year of a firm's existence, it was the mean of the number of patents applied for each year since firm entry. We included this measure of a patenting firm's technological activity at the time of a patent because we expected that technologies developed by firms perceived as highly technologically active might draw disproportionate attention from other firms. Because their innovative efforts would be more broadly observed, they would be more likely to be built upon by others (Podolny & Stuart, 1995).[4]

[3] Several data challenges compelled Hall et al. to calculate lower and upper bounds for the estimate of self-citations. We used the lower bound, although the differences are small and our results are invariant to the use of either measure. Alcácer and Gittleman (in press) noted that a large number of self-citations are paradoxically added by examiners, rather than inventors. Fortunately for our purposes, high numbers of self-citations from either source indicate that a given patent is closely related to a firm's prior technological trajectory.

[4] To avoid potential confusion, we note that our independent variables all related to information in a focal patent—that is, the number of the firm's own prior pat-

TABLE 1
Variable Definitions

Name	Definition
Dependent variable	
Citations received	The number of citations received in a given year from other firms.
Independent variables	
Firm exit	A 0/1 variable set to 1 if a firm had exited at the time of an observation.
Firm age at time of patent	The application year of a focal patent minus the year of firm founding.
Internal focus	The percentage of citations in a focal patent to other patents of the same company (labeled "selfctlb" in the NBER Patent Citations Data File)
Number of inventors	The number of inventors listed on a focal patent.
Range of technologies combined	The heterogeneity of the patent classes cited by a focal patent (labeled "original" in the NBER Patent Citations Data File).
Control variables	
Maturity of technology	The number of citations made by a focal patent divided by the number of claims it contains.
Recent technological activity	The average number of patents by a firm over the three years prior to patent application.
Application year dummies	0/1 variables for the year in which a patent was applied for in the 1977–97 period.
Citation lag	0/1 set for each of the 24 indicator variables (lag_1 to lag_24) for every year after a patent application year.

Table 2 provides the descriptive statistics and correlation matrix for the key variables in the study. An inspection of the correlations does not reveal any multicollinearity concerns, showing a mean variance inflation factor (VIF) of 1.18 and a maximum VIF of 1.58.

METHODOLOGY

Our dependent variable was the number of citations a patent received in each year after its application date, so we turned to the family of count data models for estimation (Greene, 2000). Our empirical model was similar to that of Song et al. (2003) and Rosenkopf and Almeida (2003). Although those papers measured the total citations a patent received from a given firm, we modeled the number received from all firms in each year in order to be able to estimate the effect of firm exit over time. Specifically, the probability of a patent receiving a given number of citations can be modeled as resulting from a Poisson process:

$$\Pr(Y_{it} = y) = \frac{e^{-\mu_i}\mu_i^{yi}}{y_i!}, \tag{2}$$

where Y_{it} represents the number of citations received by patent i in year t after the patent application. The mean value μ_i is parameterized in terms of $\boldsymbol{x_i}$, the vector of attributes, and coefficient vector β:

$$\mu_i = \exp(\boldsymbol{x}'_{it}\beta). \tag{3}$$

The Poisson process, however, restricts the mean and variance to be equal, which may not be a reasonable assumption. The negative binomial regression model extends the Poisson regression model by allowing the variance of the process to exceed the mean (Cameron & Trivedi, 1998). The degree by which it does so, the overdispersion parameter, equals the variance of the process divided by its mean. Because we had panel data, we used a random-effects negative binomial model (Hausman, Hall, & Griliches, 1984), which specified that all observations for a given patent i shared a common overdispersion parameter δ_i, in which $1/(1 + \delta_i) \sim \text{beta}(\alpha, \beta)$, to avoid inflated standards errors. Because many of our variables of interest were invariant within a patent, we were unable to use fixed effects. The mean dispersion was greater than 1.3 in all models, indicating a variance at least 30 percent greater than the mean (p[variance > mean] < .05), indicating in turn that the negative binomial model was more appropriate than a Poisson model.

RESULTS

We first investigated the effect of firm exit on patent citation counts to test if diffusion rates differed significantly before and after a firm's exit. For ease of exposition, we depict this effect graphically in Figure 1 and note that the results from the negative binomial model presented later are consistent with the graph. Figure 1 shows the average number of citations received from other firms by patents in each year after their application dates for three groups of patents: (1) those belonging to firms that did not exit the industry through 1997, (2) those belonging to firms that would eventually exit but had not yet done so for the relevant citation lag year, and (3) those belonging to firms that had

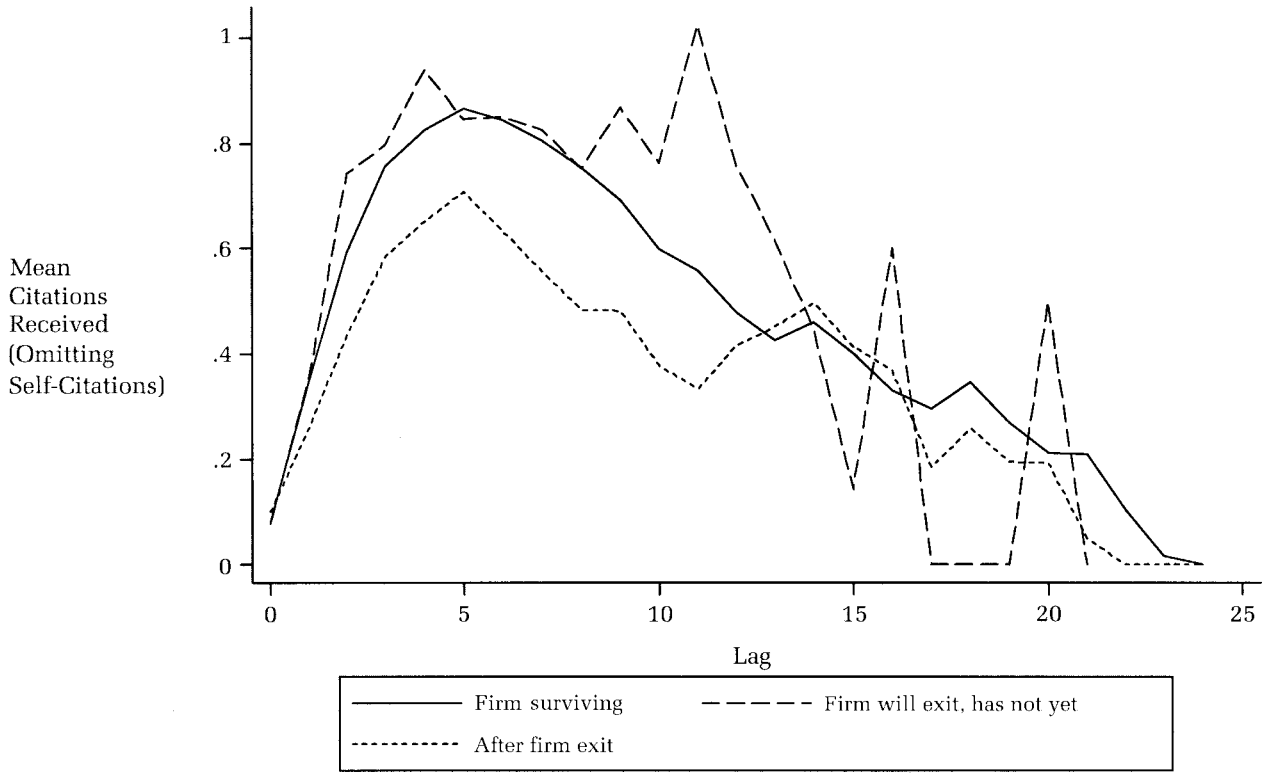
ents that it cited. Our dependent variable related to the decision by other companies to cite the focal patent subsequent to its granting.

TABLE 2
Summary Statistics and Correlations[a]

Variable	Mean	s.d.	Minimum	Maximum	1	2	3	4	5	6	7
1. Citations by other firms	0.55	1.24	0.00	28.00							
2. Firm has exited	0.22	0.41	0.00	1.00	−.04						
3. Firm age at time of patent	14.01	10.39	0.00	43.00	.02	−.37					
4. Internal focus	0.16	0.25	0.00	1.00	.01	.00	.25				
5. Number of inventors	2.46	1.79	1.00	20.00	.05	−.12	.12	.03			
6. Range of technologies combined	0.24	0.25	0.00	0.88	−.01	.04	.08	−.03	.02		
7. Maturity of technology	0.87	1.37	0.02	26.33	−.03	.03	.01	−.04	−.02	.14	
8. Recent technological activity of firm	35.72	31.78	0.00	128.00	.04	.01	.46	.27	.09	.08	.03

[a] n = 43,161. Because of the large n, every correlation is uninformatively significant at the 10 percent level or better.

FIGURE 1
Citations Received from Other Firms over Time



already exited at the time of the observation. For example, if a firm A remained in the industry in the period under study, the citations its patents received for all citation lag years were placed in the first group, "firm surviving." On the other hand, consider a firm B that filed a patent in 1980 and then exited in 1985. The citations received by this particular patent were included in the second group, "firm will exit, has not yet," until citation lag 5 (1985 for this patent) and in the third group, "after firm exit," for all subsequent citation lags.

Prior to the exits of their firms of origin, the patents of firms that eventually exited the industry received approximately the same number of citations as those of firms that remained in existence. Tests of homogeneity confirmed the visual impression gained from examining the lines shown in Figure 1: the number of citations received is indistinguishable for the first two groups ($p > .10$) for citation lags of up to ten years. The exception is the lag of two years, in which patents of firms that would exit, but had not done so yet, received sig-

nificantly more citations on average (0.74 versus 0.59, $p = .005$). Thus, patent citation counts do not differ, *while a firm is still in existence*, for firms known to have survived and firms known to have later exited. Our finding of similar diffusion rates prior to exit for exiting and surviving firms supports earlier studies that indicate that firms may exit this industry despite being technologically innovative (Golder & Tellis, 1993; Katz & Shapiro, 1985; Podolny & Stuart, 1995). It also confirms the anecdotal evidence provided by McKendrick and colleagues (2000: 73) that led them to conclude that the industry landscape is "littered with the graves" of firms that were once considered technological leaders.

Once a firm exited, however, citations to its patents dropped precipitously. As the third curve reveals, the patents of firms that had exited the industry by a citation lag year received fewer citations than either of the other two groups, and this difference is particularly stark for the earlier citation lag years. For citation lags of 1 to 11 years, the difference between the numbers of citations to the patents of firms that did not exit and to the patents of those that already had exited ranges from 18 to 40 percent (p[difference > 0] < 0.01). Citations to the patents of firms that would exit but had not already done so and citations to the patents of firms that had already exited differ at the .05 level or better for lags of 1–11 years, with the exception of the 5-year lag, with the difference ranging from 16 to 67 percent. Thus, we find evidence consistent with Hypothesis 1. In spite of this drop, citations to the patents of exited companies remained significantly above zero for most of the period ($p < .05$ for lags of 1–20 years). Firm exit, or death, has a detrimental, but not a final—or "fatal"—effect on the diffusion of knowledge to other firms. For later years, the citation count is not significantly different from the citation counts received by the other two groups. This pattern is intuitively reasonable and consistent with findings that the advantages of geographic proximity for learning about the work of others "fade as the work is used and disseminated" over time (Jaffe et al., 1993: 591).

We now turn to our formal analysis of the effect of firm exit on the relationships between citation counts and our key variables of interest. Tables 3 and 4 present the results of a negative binomial estimate of citations received from other firms. We note that the coefficients represent semielasticities—that is, the proportionate change in the conditional mean caused by a one-unit change in the explanatory variable (Cameron & Trivedi, 1998: 81–82). In Table 3, we present a simple exposition of the main effect of exit on patent citations, aggregating over potential interaction effects with citation lags (given the nonlinear pattern of patents' citation lags [e.g., Trajtenberg, 1990] observed in Figure 1) and with key explanatory variables. In Table 4, we relax this assumption and present the fully specified model, allowing for a free-functional form by

TABLE 3
Results of Negative Binomial Estimation of Citations Received before and after Exit[a]

	All Firms		Diversified Firms
Variable	**Model 1**	**Model 2**	**Model 3**
Firm age at time of patent	−0.01 (0.03)	−0.01 (0.03)	−0.01 (0.03)
Internal focus	−0.01 (0.06)	−0.01 (0.06)	−0.03 (0.06)
Number of inventors	0.03** (0.01)	0.03** (0.01)	0.03** (0.01)
Range of technologies	−0.06 (0.04)	−0.06 (0.04)	−0.08* (0.05)
Recent technological activity of firm	0.01** (0.00)	0.01** (0.00)	0.01** (0.00)
Maturity of technology	−0.03** (0.01)	−0.03** (0.01)	−0.03* (0.01)
Firm has exited		−0.06* (0.04)	−0.09* (0.04)
Constant	−0.52 (0.57)	−0.50 (0.57)	−0.43 (0.58)
Firm dummy (joint significance)	0.00**	0.00**	0.00**
Application year (joint significance)	0.00**	0.00**	0.00**
Mean dispersion	1.48**	1.48**	1.44**
Number of observations	42,927	42,927	36,426
Log-likelihood	−40,451.09	−40,449.59	−33,253.34

[a] Standard errors are in parentheses.
* $p < .05$
** $p < .01$
One-tailed tests.

TABLE 4
Negative Binomial Estimation of Citations Received, Interaction Models for before and after Exit

	All Firms						
Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Diversified Firms: Model 7**
Firm age at time of patent	−0.02 (0.42)	−0.02 (0.49)	−0.02 (0.41)	−0.02 (0.43)	−0.02 (0.42)	−0.02 (0.49)	−0.02 (0.48)
Firm age at times of patent × exit		−0.05** (0.00)				−0.05** (0.00)	−0.05** (0.00)
Internal focus	0.02 (0.78)	0.02 (0.78)	0.08 (0.25)	0.02 (0.80)	0.02 (0.76)	0.11 (0.12)	0.08 (0.32)
Internal focus × exit			−0.25* (0.04)			−0.37** (0.00)	−0.28* (0.03)
Number of inventors	0.03** (0.00)	0.03** (0.00)	0.03** (0.00)	0.03** (0.00)	0.03** (0.00)	0.03** (0.00)	0.04** (0.00)
Number of inventors × exit				−0.04* (0.03)		−0.05* (0.02)	−0.06* (0.02)
Range of technologies combined	−0.05 (0.27)	−0.05 (0.28)	−0.05 (0.30)	−0.05 (0.26)	−0.03 (0.57)	−0.03 (0.49)	−0.08 (0.14)
Range of technologies × exit					−0.10 (0.26)	−0.06 (0.50)	−0.02 (0.83)
Recent technological activity of firm	0.02** (0.00)	0.02** (0.00)	0.02** (0.00)	0.02** (0.00)	0.02** (0.00)	0.02** (0.00)	0.02** (0.00)
Maturity of technology	−0.03** (0.00)	−0.03** (0.00)	−0.03** (0.00)	−0.03** (0.00)	−0.03** (0.00)	−0.03** (0.00)	−0.03* (0.02)
Constant	−1.25* (0.04)	−1.32* (0.03)	−1.27* (0.03)	−1.26* (0.03)	−1.25* (0.04)	−1.38* (0.02)	−1.29* (0.03)
Citation lag (joint significance)	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
Exit × citation lag (joint significance)	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
Firm dummy (joint significance)	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
Application year (joint significance)	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
Mean dispersion	1.36**	1.36**	1.36**	1.36**	1.36**	1.36**	1.32**
Number of observations	43,161	43,161	43,161	43,161	43,161	43,161	36,655
Log-likelihood	−38,478.43	−38,453.01	−38,476.21	−38,476.13	−38,477.80	−38,445.53	−31,550.48
Significance of incremental chi-square over model 1		0.00**	0.03*	0.03*	0.26	0.00**	

* $p < .05$
** $p < .01$

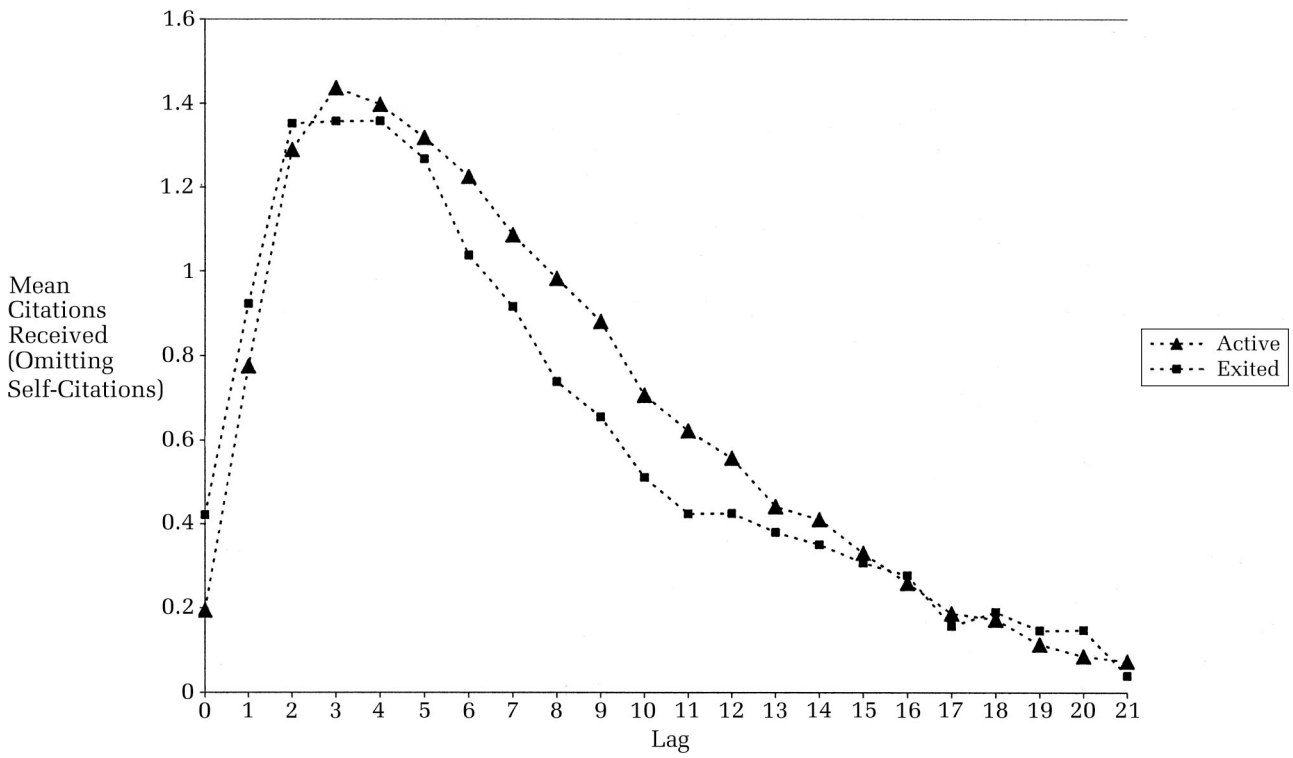
including citation lag dummies. Model 1 in Table 3 reports the results for the main effect of our explanatory variables; it does not differentiate between citations received while an innovating firm was active and citations received after its exit from the focal industry. In model 2, we include the main effect of exit, which is negative and significant, thus providing support for Hypothesis 1.

The tests of our interaction hypotheses, Hypotheses 2–5, are reported in Table 4. Model 1 reports the coefficients of the main effects. The 24 citation lag variable dummies (not reported owing to space limitations) account for time-varying effects of the citation lag years and, collectively, they are consistent with the patterns observed in Figure 1. The number of citations increases quickly, peaking around four years after a patent was applied for, and then slowly decreases.

To capture the effect of exit on the baseline, the models in Table 4 include a full set of interaction terms between exit and citation lags. The coefficients are jointly significant, though not reported owing to space limitations. Instead, Figure 2 depicts the trend in citation rates of patents before and after firm exit on the basis of the estimated coefficients in model 6 of Table 4 and computed at the mean values of the variables. Consistently with Figure 1, the total effect of exit on the average patent is negative and significant, indicating that patents received fewer citations once a patenting firm exited the industry. We note that for the first three citation lags after application year, exit has a *positive* effect on citations. However, as Jaffe, Trajtenberg, and Henderson (1993: 586, footnote 18) noted, citations to patents applied for but not yet granted are most likely the result of inclusion by a patent examiner (since the citing firm could not be aware of an ungranted patent application). In our data, the average lag between application year and grant year is 2.07 years; thus, we do not attribute any knowledge diffusion for these early years. Importantly, exit has a negative effect on citations for citation lags 3 through 17. The predicted overall impact of firm exit for a patent, at sample mean values for each covariate, is a loss of 0.05 citations per year, a 9 percent decline. Accordingly, our fully specified interaction model, model 6 in Table 4, also provides support for Hypothesis 1.

Models 2–5 in Table 4 show the results of our tests of Hypotheses 2 through 5 separately by introducing each of the interactions with exit separately, and we report the full model in column 6. With the exception of the variable "range of technologies combined," the interaction terms significantly improve the fit of the model. Our test of the first two interaction hypotheses (Hypotheses 2 and 3) re-

FIGURE 2
Impact of Exit on Citations to an Average Patent



lated to firm age and internal focus yield similar results. Neither variable is significant when a firm is active, and both have a significant, negative interaction with firm exit. Both variables are associated with more embedded innovative routines: an innovation that draws upon a firm's own knowledge base is naturally stickier than other innovations, and older firms have more established innovative routines. Our results indicate that, *when an innovating firm is active,* other firms are able to overcome these barriers through opportunities for learning from the innovating firm's activities. However, absent this template, upon firm exit, other firms find it harder to build on an initial innovation. Thus, we find support for Hypotheses 2 and 3.[5]

The coefficient of the variable measuring number of inventors is positive and significant, indicating that patents involving more inventors receive more citations. However, a significant, negative interaction with exit implies that after a firm's exit, other firms find it very difficult to build on knowledge that required larger inventor teams.[6] In particular, since a high number of inventors implies a large pool of mobile employees, the large and significant coefficient of the interaction term in model 2 underscores the need for the innovating firm to continue to exist so that other firms may observe its routines and management of innovation. This finding supports our Hypothesis 4.

Finally, we find no effect for the variable measuring the range of technologies combined or its interaction with firm exit. Thus, Hypothesis 5 is not supported. This absence of support suggests that the combination of technologies that occurs in this industry poses little challenge for imitation. Once a firm has successfully combined multiple technologies, other firms do not find it difficult to build on the resulting combined technology, with or without access to the firm as a template. We note, though, that this result may reflect the relatively low value of this variable in our sample; this value was 0.24 (in a range of 0–1). By comparison, the average over all sectors was approximately 0.30 in 1975, and it rose to approximately 0.40 in the 1990s (Hall et al., 2002: 430, Figure 15). The range of technologies combined in the hard drive industry may not have been diverse enough to pose a barrier to knowledge replication. Alternatively, it may be due to the lack of variance resulting from use of an intraclass measure for the extent of diffusion, given our single-industry focus.

Among the control variables, we find that maturity of technology is negative and significant and that recent technological activity is positive and significant. This pattern of findings accords with our expectations that patents building on mature technologies are less likely to be cited and that patents belonging to more technologically active firms are cited more heavily.

To ensure robustness of our results, we conducted several additional tests. As noted in the data description, both diversified and nondiversified (pure-play) disk drive firms operated in the industry. This distinction is particularly important, insofar as diversified firms continued to exist elsewhere once they exited the disk drive industry. Accordingly, we tested our hypotheses for the subset of diversified firms. These results are reported in model 3 of Table 3 and model 7 of Table 4. All the hypotheses continue to be supported; the only substantive change in the results is that the main effect of firm age for diversified firms is negative and significant.

We also ensured that our results were not sensitive to choice of model specification. Since most of our interaction hypotheses relate to time-invariant variables at the patent level, we were unable to run a panel-level fixed-effects specification. However, our results are robust to whether the firm-level fixed effects are included or excluded in the specification. We additionally conducted tests of our hypotheses using the Poisson model. The results for all the hypotheses remain unchanged. Further, Hypothesis 5, which relates to the range of technologies combined, is supported in the Poisson specification.

ALTERNATIVE EXPLANATIONS

Our hypotheses regarding the main and moderating effects of the exit of a firm from a technologically intensive industry on the diffusion of its knowledge centered around the importance of ac-

[5] A high rate of self-citation might also indicate a highly specialized firm that may be pursuing a line of inquiry that others do not find promising. The signal generated by firm failure might provide additional negative information regarding the approach and reduce citations. However, we note that other firms would likely not find such a line of inquiry promising, even before the failure of the firm.

[6] Given that both the main and interaction terms are statistically significant, we find that each additional inventor increases the expected number of citations by 3.4 percent when a firm is active (the coefficient on the number of inventors = 0.03) and reduces the expected number of citations by 1.6 percent when the firm has exited. (When exit = 1, the coefficient equals –0.016 [0.034 + {0.05} × 1], where –0.05 is the coefficient of the interaction term of exit and number of inventors.).

TABLE 5
Tests of Homogeneity of Firm and Patent Characteristics

	Diversified Firms			Pure-Play Firms		
Variables	**Surviving Firms**	**Exiting Firms**	***t***	**Surviving Firms**	**Exiting Firms**	***t***
Patents per year	15.70 (12.79)	5.88 (13.28)	1.87	8.06 (8.59)	1.61 (0.91)	2.12
Internal focus	0.09 (0.08)	0.04 (0.07)	1.76	0.07 (0.06)	0.01 (0.02)	2.48*
Range of technologies	0.31 (0.07)	0.26 (0.13)	1.49	0.39 (0.14)	0.26 (0.19)	1.95
Number of claims	14.91 (5.46)	11.46 (4.81)	1.62	14.46 (3.70)	11.58 (6.27)	1.52
Number of inventors	2.46 (0.97)	1.76 (0.71)	1.92	2.19 (0.74)	1.90 (0.85)	0.93
Maturity of technology	0.77 (0.24)	0.88 (0.48)	−0.83	1.33 (0.82)	1.13 (0.61)	0.65

* $p < .05$

cess to the private knowledge contained in the firm's routines. As indicated in the theory section, there may, however, be alternative explanations for the observed effects. One possibility is that differences in technological prowess caused firm exit and also manifested themselves in lower citation rates. Supporting Christensen (1993), Franco, Sarkar, Agarwal, and Echambadi (2005) found that superior technological capabilities did not enhance survival rates in the absence of firm entry into the new submarkets that developed in the disk drive industry. We do not discount the possibility that a lack of technological capabilities is positively related to exit yet see several firms in the sample that exited the industry in spite of their technological ability. Indeed, the fountainhead of knowledge and creator of the industry, IBM, ultimately ceased operations in disk drives in 2002, indicating the importance of factors beyond technological capabilities. Further, our data do not indicate that firms that exited the industry differed significantly in their patenting behavior from firms that were still in existence in 1997. Table 5 reports our tests of homogeneity for both diversified and pure-play subsets of firms. Diversified firms that exited during the period of our study and those that did not showed no statistically significant differences ($p < .05$) on the following: number of patents received per year, internal focus, range of technologies drawn upon, number of claims per patent, and number of inventors per patent. The same results hold, with the exception of internal focus, for the subset of pure-play firms. Moreover, as already indicated by Figure 1, no significant difference in citation rates was observed for the years in which firms existed between firms that remained in existence over the study period and those that eventually exited the industry. Most importantly, although differences in technological capabilities may result in differences in the overall number of patents a firm receives[7] or in the overall *level* of citations those patents receive, our hypotheses centered on the *change* in citations received by a given patent after firm exit. The quality of the knowledge underlying patents plays no role in the impact of exit; rather, we ask to what degree other companies build on a patent, *contingent on the status of the inventing firm* (surviving vs. defunct).

Another alternative explanation for the observed results could be that other firms take the exit of a company as a signal that its technology is no longer relevant, an assumption that would lead them to pay less attention to the innovations the firm generated while active. As noted in our description of the disk drive industry, the relevance of the underlying technology base in the industry did not change significantly during the time period studied (Christensen, 1993). At the firm level, although we controlled for these issues to some degree by including variables measuring the maturity of technology and recent technological activity, we could not rule out this explanation altogether for the main effect of firm exit (Hypothesis 1), since it might have driven a portion of the overall drop in citations a patent received after the exit of the firm that held it. However, the signaling of relevance driver cannot explain the effects of the interaction of firm exit with variables associated with varying degrees of private knowledge (Hypotheses 2–6). The same is true for the potential explanation that firms were less fearful of litigation on the part of source firms. In this context, we also highlight the results obtained above for the subset of diversified firms that ceased their disk-drive-related activity. Since these firms were still in existence, they were presumably

[7] We note that in Table 5, patents per year seem to be higher for surviving than exiting firms, though the high standard deviations imply that these are not statistically significant.

willing to protect their intellectual property. If a lower likelihood of litigation by firms were the main driver of the drop in citations after their exit, we should not see any significant effect of exit on the citations received by their patents. However, as noted earlier, the patenting activity in disk drives undertaken by the diversified firms dropped sharply after their exits from the industry. Thus, the evidence still points strongly to the loss of private knowledge having an important effect.

In sum, a firm's exit would taint all of its patents as inferior, less likely to be defended, or irrelevant to the same degree, yet we find that the postexit reduction in citations received for a given firm's patents is highly conditional on the characteristics of each patent—characteristics that are closely tied to the importance and inaccessibility of the private knowledge associated with that patent. Indeed, the support that we find for the interaction hypotheses, coupled with the cross-patent variation in citations of patents belonging to the same exited firm, helps rule out a wide range of alternative explanations.

DISCUSSION AND CONCLUSION

The fate of innovative knowledge created by firms that subsequently exit an industry is of practical and theoretical importance. To the degree that knowledge languishes after the exit of an innovating firm, other industry participants and society at large lose a potential source of technological progress. If, however, knowledge that a defunct firm created is significantly diffused, these positive externalities result in some social benefit from the investments made when the firm was alive. Theoretically, the fate of innovative knowledge after firm exit illuminates the impact of private knowledge on the diffusion of knowledge that is in the explicit/codified domain and the extent to which the continued existence of a firm enhances spillovers of its knowledge.

There is anecdotal evidence that a firm's innovative knowledge can outlast its existence. The introduction to this study cited OIS as an example of a firm whose knowledge had considerable impact on an industry (the flat-panel display industry) after its demise. Another such firm is Prairietek. This company was active in disk drives for only five years, but one of its patents was cited 106 times in the eight years between its exit and 1999. Our study sought to systematically study this issue and provide empirical evidence on whether OIS and Prairietek are merely exceptions to the rule or examples of a regular pattern of postexit diffusion.

Our study provides several insights regarding the effect of firm exit, or death. First, death clearly hurts knowledge diffusion. Examining the patent citation trends before and after the exit of a firm, we find a significant decline in the citation rate that was attributable to firm exit, even after controlling for firm and patent characteristics. Our results show that, in addition to the features identified in prior research as the characteristics of a firm that is the source of knowledge, another important determinant of knowledge diffusion is the continued existence of the firm. Thus, our evidence suggests that studies of knowledge diffusion should address not only the impact of the quality of knowledge on its ultimate citation but also the fate of the firm that originated the knowledge.

In this context, we note that the extent of employee mobility in the disk drive industry is so high that disk drive designers have said that "workers remain the same, they just shift periodically from company to company" (McKendrick et al., 2000: 44). Employee mobility and reverse engineering allow for continued diffusion of a firm's technology after its exit; however, these mechanisms are tempered by the inaccessibility, after firm death, of private knowledge that was embedded in the firm's organizational structure. Indeed, the exit of a firm from an industry should release many employees who can act as conduits of knowledge transfer in the organizations that subsequently hire them. As Ingram noted, "The experience of a failed organization may be particularly likely to diffuse through employee mobility as participants in the failure go to new jobs" (2002: 657). As a result, to the extent that an exited firm's knowledge resided in the human capital of individual employees (Becker, 1964), mechanisms for its continued diffusion exist. Although the possibility of knowledge transfer to other firms through employee mobility is highest at the time of firm exit, we find no evidence of increased citation by other firms after firm exit. This absence of evidence may imply that knowledge transfer through employee mobility is more effective when a source firm remains active. Recipient firms, even when they hire employees from a source firm, may still need to either interact with, or at least observe, its rules and routines in order to fully benefit from the knowledge transfer.

However, death is not fatal to knowledge diffusion. OIS and Prairietek are not just anecdotal exceptions. There is clear evidence of significant postexit diffusion of knowledge. Indeed, our findings are consistent with findings about social welfare enhancement reported by Knott and Posen, who found that knowledge spillovers from exited firms were associated with reduction in the costs of surviving firms. Thus, although citation rates did decline after firm exit, firms that exited still received

a significant proportion of the citations that they could have expected to receive had they still existed. Further, death may also not have a permanent impact on diffusion, since we found that differences in the diffusion of active and defunct firms' knowledge faded over time. Taken cumulatively, the pre- and postexit citations received by the patents of firms that ultimately exited the disk drive industry imply that the firms provided significant welfare benefits to society.

Our study is limited in many respects. As in all studies that employ data from single industries, our results may not be generalizable to other industries that have very different conditions from those in our focal industry. In our use of patent data, our study is also subject to the limitations recognized in the literature, including the view that patents may not represent all inventive activity in an industry. In particular, although several thousand patents were granted to the firms in the disk drive industry, we do not know the exact proportion of the total inventions in the industry that these patents represent. Further, given our focus on whether an inventing firm existed or had exited, and the empirical design of counting all citations received by each patent, we did not distinguish between recipient firm characteristics and the mechanisms employed for knowledge transfer. Also, given time-invariant explanatory variables, we could not test our hypotheses using a fixed-effects specification and had to assume random effects when controlling for patent-level unobserved heterogeneity. Further, although we identified and tried to address several alternative explanations for the observed main effect of exit and included firm-level fixed effects to control for firm-level unobserved variation, we were not able to disentangle the relative effects of all the potential explanations and the extent to which changes in the status and relevance of technologies, along with type of firm (e.g., specialist vs. generalist) might have impacted the postexit diffusion of knowledge. Knowledge belonging to firms that exit because of a lack of complementary assets may be of greater postexit interest to others than knowledge belonging to firms that fail because of technological weakness, but we could not isolate the cause of each firm's exit.

Both the results from our study and its limitations point to several intriguing questions for future research. As we noted at the outset, given our interest in identifying how private knowledge complements public knowledge, our study highlighted the impact of firm exit on knowledge that is explicit and codified in patents. We suspect that firm exit has an even more detrimental impact on tacit and noncodified knowledge, resulting not just in a decline in diffusion, but also in an actual *loss* of knowledge. For instance, MacKenzie and Spinardi (1995) presented evidence on the "uninvention" of tacit knowledge in the nuclear weapons industry that resulted from cessation of design and operations. Similarly, Benkard (2000) found evidence of organizational "forgetting" in the presence of highly tacit and human-capital-embodied knowledge. Future research assessing the impact of firm exit on other types of knowledge, particularly those with high tacitness, would help shed further light on this issue.

Our results relate to the "average" effect of firm exit on knowledge diffusion and, in particular, our study does not address the impact of heterogeneity in *recipient* firms' capabilities and strategies on the postexit diffusion of knowledge created by a source firm. Future research needs to examine heterogeneity in the use and further development of technologies created by firms that exit an industry. In view of our findings, we expect that absorptive capabilities (Cohen & Levinthal, 1990) will play an especially important role. In the absence of an observable template, firms with a greater ability to dissect and absorb innovative knowledge on their own will have an advantage in building on a departed firm's knowledge. Relatedly, future research could distinguish among recipient firms on the basis of location relative to source firm and compare the effects of source firm exit on knowledge diffusion to colocated and distant recipients. Doing so would also enable scholars to address whether potential geographical effects are a result of language/cultural issues or a more systematic challenge associated with transferring technologies over geographic distances.

Further studies are also needed to understand the mechanisms underlying knowledge transfer and whether firms should use different strategies when seeking knowledge from existing versus defunct firms. Such studies would have important managerial implications as well. Learning vicariously and forming a collaborative networks are not options for learning from firms that have exited an industry; mechanisms for transferring technology from defunct firms may instead include hiring technical employees (Rosenkopf & Almeida, 2003), hiring managers (Boeker, 1997), and buying intellectual property (Arora, Fosfuri, & Gambardella, 2001). Intellectual property, although useful, transfers only formal, public knowledge, omitting associated private, tacit know-how that may be critical. Technical employees bring both explicit and tacit knowledge to a new firm, but they are removed from the routines and culture of their previous employer. Managerial employees bring important organiza-

tional knowledge that can help in the re-creation of team dynamics and routines. Are these mechanisms more or less effective when a firm that is the source of knowledge is still in existence or when it has exited? Should the technology strategy for harnessing knowledge created by a departed firm focus on one more than the others, or is it more effective to combine multiple mechanisms?

Our study has demonstrated that private knowledge matters, but isolating the impact of private knowledge held at various levels in firms (individual inventors, research teams, routines for achieving complementarity in resources) was beyond its scope. We hope that future research will theorize and test the implications of these distinctions and disentangle the effects that private knowledge at each level may have on subsequent diffusion. For instance, is there greater diffusion of knowledge when the individual inventors scatter to different firms, each providing a seed for distinct trajectories that build on an exited firm's knowledge, or is there greater diffusion when all inventors move as a team, thereby preserving some of the knowledge held at the team level? If the latter is the case, what are some impediments to collective movement of teams from one firm to another, and how may these be addressed?

In conclusion, we find that stickiness owing to embeddedness is a major impediment to diffusion of knowledge, and our study highlights the importance of using a firm's activities as a template for successfully replicating and extending its innovative knowledge. By establishing that the private knowledge held by a firm is an important complement to knowledge in the public domain and aids in its diffusion, we have added another important dimension to the study of knowledge diffusion. Further, we believe our results have significant implications for public policy and technology strategy, particularly in highly entrepreneurial industries.

Innovative and entrepreneurial firms provide benefits to society that outlast their existence; thus, public policy aimed at encouraging their activities will provide spillover benefits that go beyond those measured through simple measures of their individual productivity and growth. Thus, evaluation of public investment in technology development should include the longer-term impact of the technology developed, independent of the commercial success of a funded firm. However, given the loss of private knowledge incurred when a funded firm fails, it would be useful to impose as a condition of public funding a requirement that firms codify their innovative knowledge to preserve it against the possibility of firm failure. Combining a better understanding of exited firms' potential contribution to society with actions to encourage postfailure diffusion of knowledge might allow funding agencies to consider funding riskier, more entrepreneurial projects than would otherwise appear optimal. To the degree that these projects are embedded in younger and smaller firms, our results suggest that the value of the knowledge they create will be more robust to the possible failure of the firms.

The obvious implication of our findings for technology strategy is that firms should actively incorporate failed or failing companies in the sources of innovation from which they draw. Beyond that, our findings give guidance regarding what specific innovations are most amenable to incorporation—those stemming for young companies, not overly embedded in a failed firm's idiosyncratic knowledge base, and having a smaller team of inventors. Future research will help us move beyond these general principles to understand what types of innovations are most amenable to incorporation by a given company with specific characteristics.

REFERENCES

Agrawal, A., Cockburn, I., & McHale, J. 2003. ***Gone but not forgotten: Labor flows, knowledge spillovers, and enduring social capital*** (Working paper no. 9950, National Bureau of Economic Research). http://papers.nber.org/papers/w9950.

Agarwal, R., Echambadi, R., Franco, A., & Sarkar, M. B. 2004. Knowledge transfer through inheritance: Spin-out generation, development and survival. ***Academy of Management Journal,*** 47: 501–522.

Agarwal, R., & Gort, M. 1996. The evolution of markets and entry, exit and the survival of firms. ***Review of Economics and Statistics,*** 69: 567–574.

Alcácer, J., & Gittelman, M. 2006. How do I know what you know? Patent examiners and the generation of patent citations. ***Review of Economics and Statistics.*** 83: 774–779.

Almeida, P., & Kogut, B. 1999. Localization of knowledge and the mobility of engineers in regional networks. ***Management Science,*** 45: 905–917.

Anderson, P., & Tushman, M. L. 1990. Technological discontinuities and dominant designs—A cyclical model of technological change. ***Administrative Science Quarterly,*** 35: 604–633.

Anton, J. J., & Yao, D. A. 2002. The sale of ideas: Disclosure, property rights, and incomplete contracts. ***Review of Economic Studies,*** 69: 513–531.

Arora, A., Fosfuri, A., & Gambardella, A. 2001. ***Markets for technology: The economics of innovation and corporate strategy.*** Cambridge, MA: MIT Press.

Arrow, K. J. 1962. Economic welfare and the allocation of resources for invention. In R. R. Nelson (Ed.), ***The rate and direction of inventive activity: Economic***

and social factors. Princeton, NJ: Princeton University Press.

Arrow, K. J. 1974. ***The limits of organizations.*** New York: Norton.

Arrow, K. J. 1996. Technical information and industrial structure. ***Industrial and Corporate Change,*** 5: 645–652.

Audretsch, D. B., & Feldman, M. P. 1996. R&D spillovers and the geography of innovation and production. ***American Economic Review,*** 86: 630–640.

Becker, G. S. 1964. ***Human capital: A theoretical and empirical analysis with special reference to education.*** New York: Columbia University Press.

Benkard, C. L. 2000. Learning and forgetting: The dynamics of aircraft production. ***American Economic Review,*** 90: 1034–1054.

Boeker, W. 1997. Executive migration and strategic change: The effect of top manager movement on product-market entry. ***Administrative Science Quarterly,*** 42: 213–236.

Burt, R. S. 1992. ***Structural holes.*** Cambridge, MA: Harvard University Press.

Caballero, R. J., & Jaffe, A. B. 2002. How high are the giants' shoulders: An empirical assessment of knowledge spillovers and creative destructure in a model of economic growth. In A. B. Jaffe & M. Trajtenberg (Eds.), ***Patents, citations, and innovations: A window on the knowledge economy:*** 89–152. Cambridge, MA: MIT Press.

Cameron, A. C., & Trivedi, P. K. 1998. ***Regression analysis of count data.*** Cambridge, U.K.: Cambridge University Press.

Chesbrough, H. W., & Teece, D. J. 1996. When is virtual virtuous? Organizing for innovation. ***Harvard Business Review,*** 74(1): 65–71+.

Christensen, C. 1993. The rigid disk drive industry: A history of commercial and technological turbulence. ***Business History Review,*** 67: 531–588.

Christensen, C. 1997. ***The innovator's dilemma: When new technologies cause great firms to fail.*** Boston: Harvard Business School Press.

Cockburn, I. M., Kortum, S., & Stern, S. 2002. ***Are all patent examiners equal? The impact of examiner characteristics,*** NBER working paper no. w8980, National Bureau of Economic Research, Cambridge, MA.

Cohen, W. M., & Levinthal, D. A. 1990. Absorptive capacity: A new perspective on learning and innovation. ***Administrative Science Quarterly,*** 35: 128–152.

Cowan, R., David, P. A., & Foray, D. 2000. The explicit economics of knowledge codification and tacitness. ***Industrial and Corporate Change,*** 9: 211.

Cyert, R. M., & March, J. G. 1963. ***A behavioral theory of the firm.*** Englewood Cliffs, NJ: Prentice-Hall.

Dosi, G., Teece, D. J., & Winter, S. G. 1992. Toward a theory of corporate coherence. In G. Dosi, R. Giannetti, & P. M. Toninelli (Eds.), ***Technology and enterprise in a historical perspective:*** 185–211. Oxford, U.K.: Oxford University Press.

Dunne, T., Roberts, M. J., & Samuelson, L. 1988. Patterns of entry and exit in the U.S. manufacturing industries. ***Rand Journal of Economics,*** 19: 495–515.

Dyer, J. H., & Singh, H. I. 1998. The relational view: Cooperative strategies and sources of interorganizational competitive advantage. ***Academy of Management Review,*** 23: 660–679.

Franco, A., Sarkar, M., Agarwal, R., & Echambadi, R. 2006. ***The moderating effect of technological capabilities on timing of entry.*** Academy of Management Best Paper Proceedings.

Golder, P. N., & Tellis, G. J. 1993. Pioneer advantage: Marketing logic or marketing legend? ***Journal of Marketing Research,*** 30: 158–170.

Gort, M., & Klepper, S. 1982. Time paths in the diffusion of product innovations. ***Economic Journal,*** 92: 630–653.

Granovetter, M. S. 1985. Economic action and social structure: The problem of embeddedness. ***American Journal of Sociology,*** 91: 481–510.

Greene, W. H. 2000. ***Econometric analysis*** (4th ed.). Upper Saddle River, NJ: Prentice-Hall.

Griliches, Z. 1979. Issues in addressing the contributions of R&D to productivity growth. ***Bell Journal of Economics,*** 19: 92–116.

Gulati, R. 1998. Alliances and networks. ***Strategic Management Journal,*** 19: 293–317.

Hall, B. H., Jaffe, A. B., & Trajtenberg, M. 2002. The NBER patent citation data file: Lessons, insights and methodological tools. In A. B. Jaffe & M. Trajtenberg (Eds.), ***Patents, citations and innovation: A window on the knowledge economy:*** 403–460. Cambridge, MA: MIT Press.

Haunschild, P. R., & Miner, A. S. 1997. Modes of interorganizational imitation: The effects of outcome salience and uncertainty. ***Administrative Science Quarterly,*** 42: 472–500.

Hausman, J., Hall, B. H., & Griliches, Z. 1984. Econometric models for count data with an application to the patents–R and D relationship. ***Econometrica,*** 52: 909–938.

Henderson, R., Jaffe, A., & Trajtenberg, M. 2005. Patent citations and the geography of knowledge spillovers: A reassessment—Comment. ***American Economic Review,*** 95: 461–464.

Ingram, P. 2002. Interorganizational learning. In J. A. C. Baum (Ed.), ***Blackwell companion to organizations:*** 652–663. Malden, MA: Blackwell.

Jaffe, A. 1986. Technological opportunity and spillovers of R & D: Evidence from firms' patents, profits, and

market value. ***American Economic Review,*** 76: 984–1001.

Jaffe, A. B., & Trajtenberg, M. 1996. Flows of knowledge from universities and federal laboratories. ***Proceedings of the National Academy of Sciences,*** 93: 12671–12677.

Jaffe, A. B., & Trajtenberg, M. 2002. ***Patents, citations, and innovations: A window on the knowledge economy.*** Cambridge, MA: MIT Press.

Jaffe, A. B., Trajtenberg, M., & Fogarty, M. S. 2002. The meaning of patent citations: Report on the NBER/Case-Western Reserve survey of patentees. In A. Jaffe & M. Trajtenberg (Eds.), ***Patents, citations and innovations:*** 379–402. Cambridge, MA: MIT Press.

Jaffe, A. B., Trajtenberg, M., & Henderson, R. 1993. Geographic localization of knowledge spillovers as evidenced by patent citations. ***Quarterly Journal of Economics,*** 108: 577–598.

Jovanovic, B., & MacDonald, G. 1994. The life cycle of a competitive industry. ***Journal of Political Economy,*** 102: 322–347.

Katila, R., & Ahuja, G. 2002. Something old, something new: A longitudinal study of search behavior and new product introduction. ***Academy of Management Journal,*** 45: 1183–1195.

Katz, M. L., & Shapiro, C. 1985. Network externalities, competition, and compatibility. ***American Economic Review,*** 75: 424–440.

King, A. A., & Tucci, C. L. 2002. Incumbent entry into new market niches: The role of experience and managerial choice in the creation of dynamic capabilities. ***Management Science,*** 48: 171–186.

Knott, A. M., & Posen, H. E. 2005. Is failure good? ***Strategic Management Journal,*** 26: 617–641.

Lanjouw, J. O., & Schankerman, M. 2003. Enforcement of patent rights in the United States. In W. M. Cohen & S. A. Merill (Eds.), ***Patents in the knowledge-based economy:*** 145–179. Washington, DC: National Academies Press.

Lerner, J. 1997. An empirical exploration of a technology race. ***RAND Journal of Economics,*** 28: 228–247.

Levitt, B., & March, J. G. 1988. Organizational learning. In W. R. Scott (Ed.), ***Annual review of sociology,*** vol. 14: 319–340. Palo Alto, CA: Annual Reviews.

Lippman, S. A., & Rumelt, R. P. 1982. Uncertain imitability: An analysis of interfirm differences in efficiency under competition. ***Bell Journal of Economics,*** 13: 418–438.

MacKenzie, D., & Spinardi, G. 1995. Tacit knowledge, weapons design, and the uninvention of nuclear weapons. ***American Journal of Sociology,*** 101: 44.

Mann, R. J. 2005. An empirical investigation of liquidation choices of failed high-tech firms. ***Washington University Law Quarterly,*** 82: 1375–1444.

March, J. 1991. Exploration and exploitation in organizational learning. ***Organization Science,*** 2: 71–87.

Martin, X., & Mitchell, W. 1998. The influence of local search and performance heuristics on new design introduction in a new product market. ***Research Policy,*** 26: 753–771.

McKendrick, D. G., Doner, R. F., & Haggard, S. 2000. ***From Silicon Valley to Singapore: Location and competitive advantage in the hard disk drive industry.*** Stanford, CA: Stanford University Press.

Nelson, R. R. 1990. ***What is public and what is private about technology?*** CCC working paper 90-9, University of California Center for Research in Managements, Berkeley, CA.

Nelson, R. R., & Romer, P. M. 1996. Science, economic growth, and public policy. ***Challenge,*** 9(2): 9–21.

Nelson, R. R., & Winter, S. G. 1982. ***An evolutionary theory of economic change.*** Cambridge, MA: Belknap.

Pfeffer, J. 1981. Management as symbolic action: The creation and maintenance of organizational paradigms. In L. L. Cummings & B. Staw (Eds.), ***Research in organizational behavior,*** vol. 3. Greenwich, CT: JAI Press.

Podolny, J. M., & Stuart, T. E. 1995. A role-based ecology of technological change. ***American Journal of Sociology,*** 100: 1224–1260.

Rosenberg, N. 1982. ***Inside the black box: Technology and economics.*** Cambridge, U.K.: Cambridge University Press.

Rosenkopf, L., & Almeida, P. 2003. Overcoming local search through alliances and mobility. ***Management Science,*** 49: 751–766.

Rumelt, R. 1984. ***Towards a strategic theory of the firm.*** Englewood Cliffs, NJ: Prentice-Hall.

Schilling, M. A. 2006. ***Strategic management of technological innovation*** (2nd ed.). New York: McGraw-Hill.

Schulz, M. 2003. Pathways of relevance: Exploring inflows of knowledge into subunits of multinational corporations. ***Organization Science,*** 14: 440–459.

Song, J., Almeida, P., & Wu, G. 2003. Learning-by-hiring: When is mobility more likely to facilitate inter-firm knowledge transfer? ***Management Science,*** 49: 351–365.

Sorensen, J. B., & Stuart, T. E. 2000. Aging, obsolescence, and organizational innovation. ***Administrative Science Quarterly,*** 45: 81–112.

Spence, M. 1984. The learning curve and competition. ***Bell Journal of Economics,*** 12: 49–70.

Szulanski, G. 1996. Exploring internal stickiness: Impediments to the transfer of best practice within the firm. ***Strategic Management Journal,*** 17: 27–43.

Teece, D. J. 1986. Profiting from technological innova-

tion: Implications for integration, collaboration, licensing, and public policy. ***Research Policy,*** 15: 285–305.

Thompson, P., & Fox-Kean, M. 2005. Patent citations and the geography of knowledge spillovers: A reassessment. ***American Economic Review,*** 95: 450–460.

Trajtenberg, M. 1990. A penny for your quotes: Patent citations and the value of innovations. ***Rand Journal of Economics,*** 21: 172–187.

Trajtenberg, M., Henderson, R. M., & Jaffe, A. B. 1997. University versus corporate patents: A window on the basicness of invention. ***Economics of Innovation and New Technology,*** 5(1): 19–50.

Valentin, F., & Jensen, R. L. 2002. Reaping the fruits of science. ***Economic Systems Research,*** 14: 363–388.

Van de Ven, A. H. 1986. Central problems in the management of innovation. ***Management Science,*** 32: 590–608.

von Hippel, E. 1994. "Sticky information" and the locus of problem solving: Implications for innovation. ***Management Science,*** 40: 429–439.

Winter, S. G. 1987. Knowledge and competence as strategic assets. In D. J. Teece (Ed.), ***The competitive challenge: Strategies for industrial innovation and renewal:*** 159–184. Cambridge, MA: Ballinger.

Winter, S. G., & Szulanski, G. 2001. Replication as strategy. ***Organization Science,*** 12: 730–743.

Ziedonis, R. H. 2004. Don't fence me in: Fragmented markets for technology and the patent acquisition strategies of firms. ***Management Science,*** 50: 804–820.

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